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UK–China Science Bridge – Sustainable solutions for the built environment

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HIGHLIGHTS

- Significant research synergy exists between UK and China in the field of sustainable solutions for the built environment.
- Considerable opportunity exists to deploy UK-based knowledge to leading Chinese universities and research institutions.
- Proof-of-concept studies in China confirmed the applicability of UK-based tests for structural durability assessment.
- The reported work is aimed at enhancing the structural health performance of concrete bridges in marine environments.
- The international collaborative programme described is of interest and benefit to other organisations active in this field.

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ABSTRACT

The remit of the UK–China Science Bridge is to accelerate deployment of research knowledge in sustainable solutions for the built environment developed at Queen's University Belfast, to high-ranking partner universities and research institutions in China. To achieve this, proof of concept studies are being undertaken at key Chinese universities and research centres to assess the relevance and transferability of Queen's University-developed technologies. Particular attention is given to non-destructive testing and sensors for monitoring the durability of structures as well as a novel form of construction called 'flexible arch'. Chinese counterparts aim to set up monitoring systems in concrete bridges using sensor systems from Queen's. Data from these monitoring stations will be used to predict the service life and structural health performance of concrete bridges in marine environments. The aim of this paper is to introduce this international collaborative programme and research, allowing other organisations to benefit from the outcomes.

1. Introduction

In 2006, the UK government introduced financial support for UK institutions with existing research links to world-class universities and high-tech businesses in selective partnering countries. The remit of funded collaborations, or Science Bridges, has been to accelerate deployment of research knowledge, deepen and strengthen current research links, undertake proof-of-concept studies, enable acquisition of new skills, and encourage wealth creation by improving the transfer of research and expertise from the research base to businesses and other users.

With an initial focus on partnerships between the UK and US, the most recent round of Science Bridge awards extended to include the emerging super-economies of China and India. In 2008, three awards apiece were funded with the US and India and four with China. With 42 applications, compared to 26 and 20 for the US and India respectively, competition for UK–China Science Bridge awards was intense. Selected in collaboration with the Chinese Ministry of Science and Technology, the four winning UK-China bridges received funding totalling £4.412 million over 3 years from the Research Councils UK.

Led by research teams from the Schools of Electronics, Electrical Engineering and Computer Science (EEECS) and Planning, Architecture and Civil Engineering (SPACE), a team from Queen's University Belfast successfully secured one of the four UK–China Science Bridge awards. Table 1 gives details of project partners in the Queen's University's UK–China Science Bridge project. With a dual focus of developing innovative and sustainable solutions relating to energy production and the built environment, this is the sole Science Bridge project, from all 10 awarded between China, India and the US, with a construction focus. The remit of this paper is to provide an overview of the built environment-related element of Queen's University's UK–China Science Bridge project. Partners

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Table 1
Project partners for Queen's University's UK–China Science Bridge project.

UK	China
Academic	
Queen's University Belfast	Chongqing University
School of Planning, Architecture and Civil Engineering	(Hunan University)
(School of Electronics, Electrical Engineering and Computer Science)	Shanghai Jiao Tong University
	(Shanghai University)
	(Southeast University)
	Tsinghua University
	Zhejiang University
Research institutions	
	Central Research Institute of Building and Construction
	Research Institute of Highways, Ministry of Transport
	(Chinese Academy of Sciences Institute of Electrical Engineering)
Industrial	
Amphora non-destructive testing Ltd.	China State Construction Engineering Corporation
Macrete Ltd.	China State Railway Construction Group
(SUPERGEN partners)	(Shanghai Bao Steel Group Corporation Ltd.)
	(Shanghai Electric Group Corporation Ltd.)

not relevant to this element of the project are shown in brackets in Table 1.

2. Need for a built environment-related Science Bridge

2.1. Chinese construction industry

With one of the fastest growth rates in the world, the outlook for the $5 trillion construction industry in China is strong. A rapidly expanding domestic economy, continuing efforts to upgrade physical infrastructure, sustained strength in foreign investment funding, healthy demand for Chinese manufactured goods, ongoing urbanisation and further population and household growth are all responsible for the spends in the construction market [1]. Infrastructure is predicted to be the fastest growing sector up to and beyond 2012, with growth fuelled by government initiatives to expand and upgrade the country's physical infrastructure; in particular its highways, railways and subway systems. Utilities construction will also dominate, as the government continues to increase the country's power generation capacity and improve electricity transmission networks, as well as expand and improve municipal water supply coverage and natural gas distribution.

2.2. Sustainable development

The combination of rapid economic growth, high rates of urbanisation and energy demand poses significant challenges for China in terms of sustainable development. China is currently the largest producer and consumer of steel, cement, and coal and owing to its heavy reliance on the latter, is the second largest producer of greenhouse gases after the USA. Recent statistics show that China overtook the USA in CO_2 emissions in 2007, with a figure of 1.802 billion ton of CO_2 in total, which is an increase of 105% from 1996 [2]. Encouragingly, however, not only is sustainable development official government policy in China, but it is also being implemented in some regions at a pace that far outstrips anything seen in Europe. Driven, in part, by China's goal of achieving a 'green' Olympics in 2008, the Chinese government strengthened environmental legislation and reported planned investments of around $12 billion in the period 1998–2007 [3]. According to Malhotra [2], China tops investment on green energy technologies. Indeed, the Chinese 11th Five-Year Plan considers innovation and sustainability in the built environment to be crucial for achieving universal sustainable development. The plan clearly identifies the need to change the mode of economic growth, make resource conservation a basic national policy, build a resource-efficient and environmentally friendly society, promote economic development in harmony with population, resources and the environment, and achieve sustainable development [4].

2.3. Role of the built environment

The volume of concrete currently being placed in China exceeds that at any other time in human history; 700 million tons of cement were manufactured and consumed in China in 2002, representing about half of global output. However, partly due to a focus on high-speed construction, premature deterioration of reinforced concrete structures in China is commonplace, as evidenced by extensive damage caused in recent earthquakes. A specific example reported in the literature includes the section of freeway concrete pavement between Shenzhen and Shantou in south China, which experienced considerable levels of cracking and deterioration after only 6–12 months [5]. With the built environment representing approximately 50% of China's national wealth, these durability issues have serious economic consequences and, perhaps not surprisingly, a direct link between durability of concrete structures and sustainable development is reported in the literature [5].

3. Scope of work

The primary aim of the UK–China Science Bridge project is to assist Chinese partners in addressing infrastructure-related issues in a sustainable manner, without hindering economic progress. Concurrently, the aim for UK partners is to benefit from enhanced uptake of technologies, knowledge and expertise through business opportunities and strengthened collaboration with key Chinese institutions and companies. Against this background, the scope of the project is broken down into five principal activities as highlighted in Fig. 1 and discussed below.

3.1. Activity 1: Proof-of-concept testing

Due to documented premature durability problems of concrete structures in China, demand exists for simple, reliable in situ tests to assess and improve quality control. For this purpose, Activity 1 will assess the appropriateness of three instruments developed at Queen's University; namely the Autoclam [6], Permit [7] and Limpet [8] tests. Co-funded by Chinese agencies and undertaken as sub-contracts to Queen's University's Science Bridge project, proof-of-concept programmes will be carried out in China by Tsinghua University, Zhejiang Universities and the Central Research Institute of Building and Construction (CRIBC). The intention of this work will be to assess the reliability and repeatability of the test methods; develop relationships between on site tests and existing laboratory-based tests covered by Chinese Standards; and to prepare documentation to support the acceptance and standardisation of these test methods in China. This China-based work will be supported by research at Queen's University focusing on applications in specialised areas, such as the assessment of surface treatments and high performance materials.

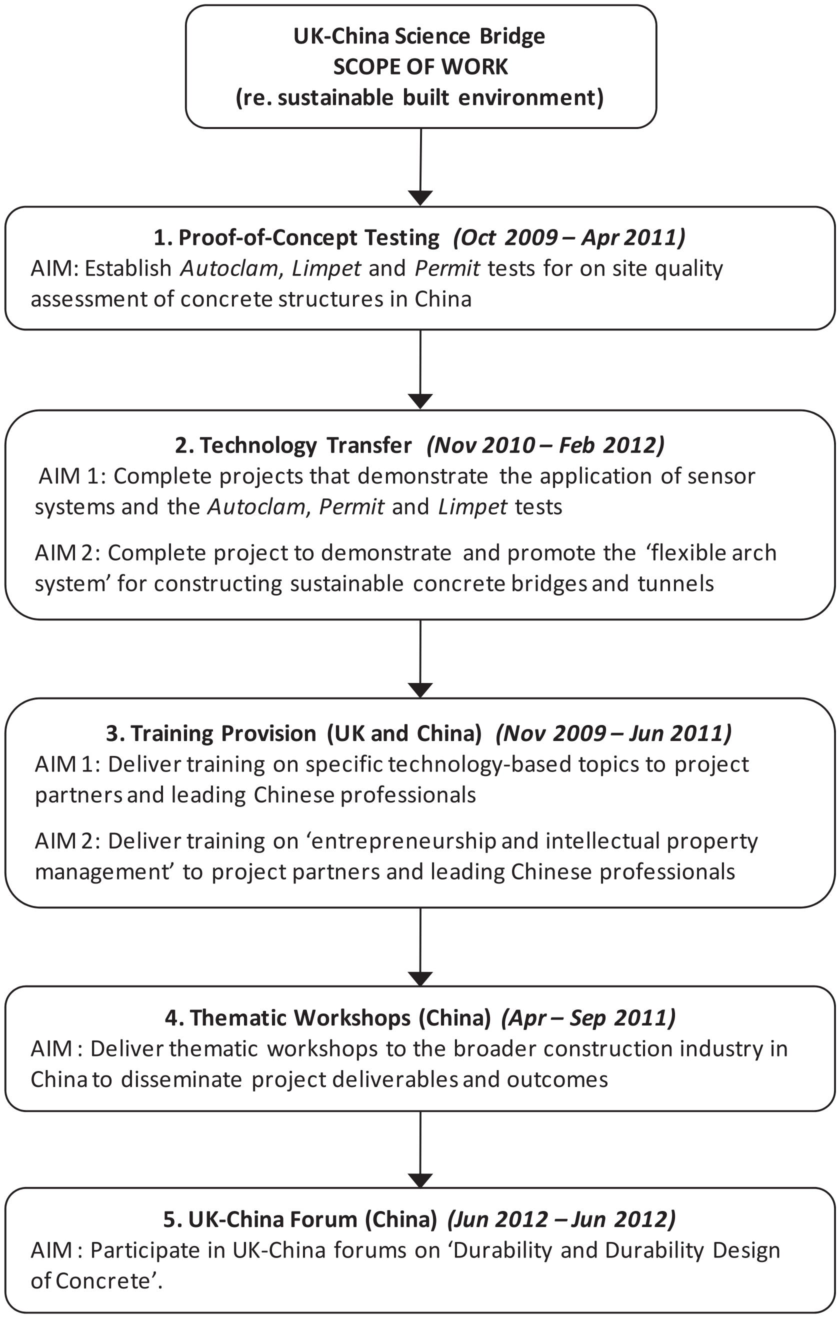


Fig. 1. Overview of UK–China Science Bridge project.

3.2. Activity 2: Technology transfer activities

The goal of this work is to promote uptake of UK-developed test methods and technologies through the delivery of demonstration projects in China. In addition to demonstrating the Autoclam, Permit and Limpet tests, novel sensor systems for monitoring reinforced concrete structures and a flexible arch system developed by Queen's University will be included in this work. Working in collaboration with Chinese partners, including the CRIBC, China State Railway Construction Group Corporation Ltd., China State Construction Engineering Corporation and Zhejiang University, the test methods for assessing in situ quality of concrete will be demonstrated on the 'Beijing to Shanghai high speed railway' and selected sea bridge' projects. The 'flexible arch' demonstration project will also be undertaken in collaboration with Zhejiang University, Chongqing University and relevant industrial partners. The ultimate aim of this work is to encourage the uptake of these instruments and technology by the Chinese construction industry.

3.3. Activity 3: Training programmes

As successful technology transfer requires industry to accept new concepts and technology and for individuals to equip themselves with relevant skills, Activity 3 will involve training packages aimed at leading Chinese professionals. Initially delivered in the UK with a primary focus on Queen's University-developed technology, this activity will expand to encompass events in China and the development of on-going training programmes aimed at professionals in both the UK and China.

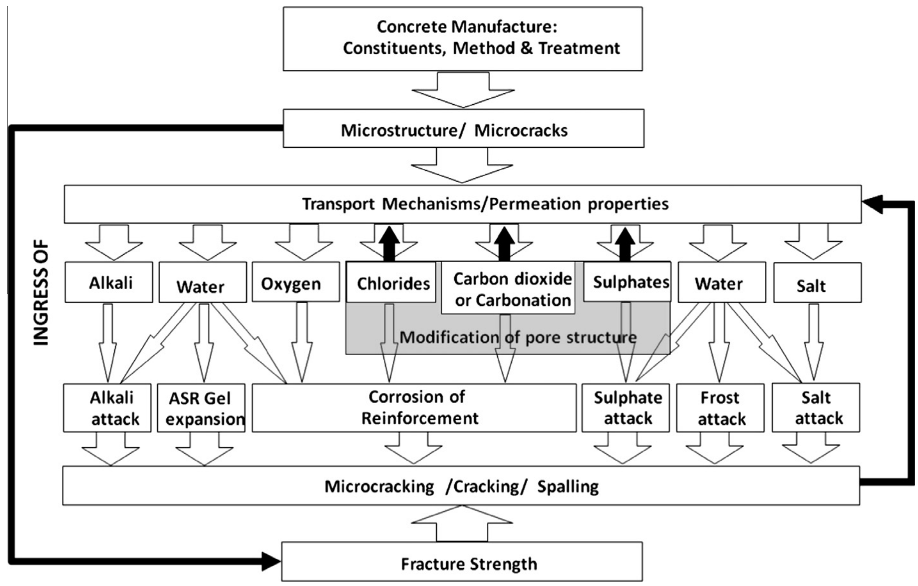


Fig. 2. Interdependence of microstructure, permeability, fracture strength and deterioration of concrete [12].

In addition to infrastructure-specific topics, training delivered as part of Activity 3 will cover 'entrepreneurship and intellectual property management'. With a long-standing tradition of providing excellent training in this field to students and with high success rates in terms of spin-out companies and national business plan competitions, Queen's University is well placed to deliver this package of training. Technology transfer internships will additionally be offered to Chinese partners to undergo training at Queen's University on relevant topics.

3.4. Activity 4: Thematic workshops

In addition to delivering training to leading professionals and project partners, the scope of Activity 4 will be broadened to disseminate project outcomes to the wider construction industry and public to ensure complete and successful technology transfer. Thematic workshops entitled 'Durability of concrete structures' (addressing mechanisms of deterioration, measures to extend service life and investigation techniques and sustainable and low carbon systems for novel arch construction), will be held in collaboration with the CRIBC, assisted by Tsinghua University, and Chongqing and Zhejiang Universities respectively.

3.5. Activity 5: UK–China forum

To enable continuation of the required breadth and depth of the UK–China collaboration and associated knowledge transfer activities, an international forum entitled 'Durable Built Environment' will be delivered along with Chinese partners. This forum will also allow policy makers to be informed of continued developments in the field of sustainable solutions in the built environment.

4. Technologies offered

As illustrated in Fig. 2, concrete deterioration is typically initiated by various environmental agents interacting, often concurrently, with cement hydrates. The onset of deterioration and the extent of subsequent micro-cracking, cracking and/or spalling is influenced by concrete's permeation properties (such as sorptivity, permeability and diffusivity) and its resistance to fracture. Clearly, the use of appropriate in situ, non-destructive tests and/or embedded or retrofitted sensors to measure concrete properties relating to deterioration offers engineers ability to monitor structures on a continuous basis to inform repair- and rehabilitation-related interventions.

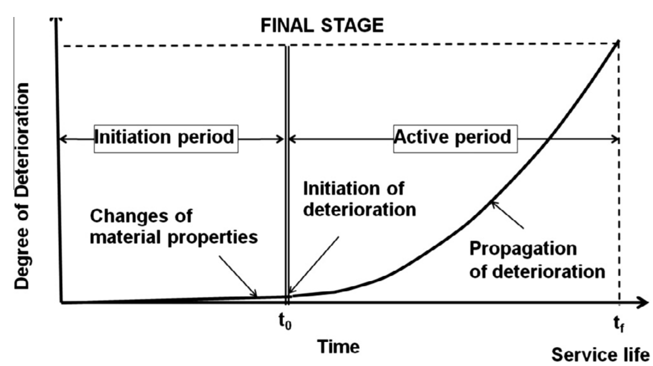


Fig. 3. Components of service life of a concrete structure [13].

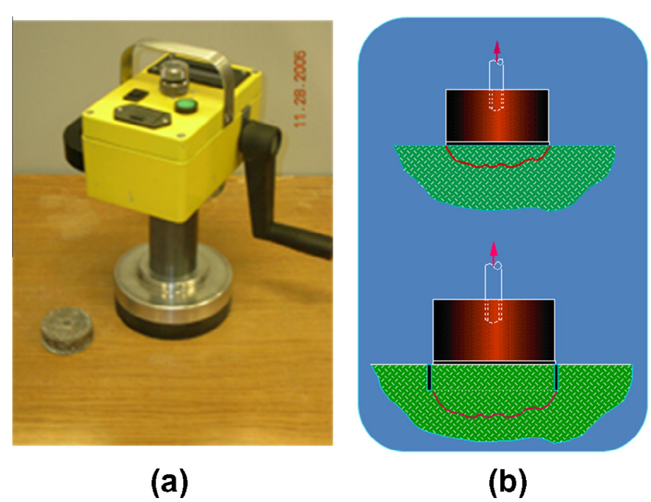
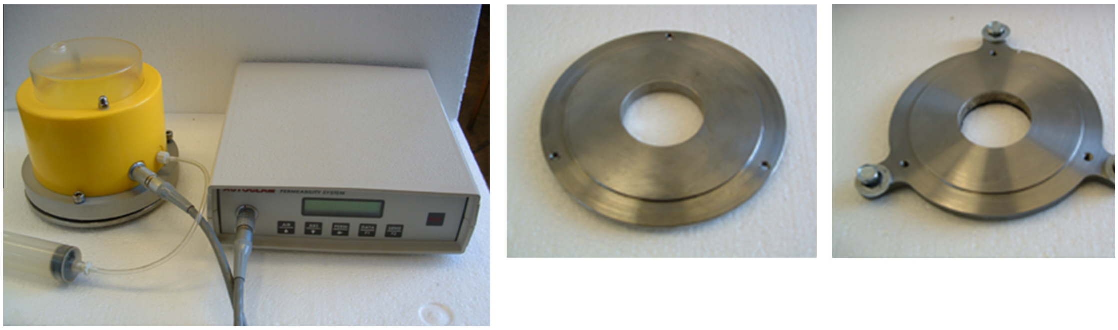


Fig. 4. Limpet pull-off tester (a) and its modes of application (b).



(a) (b) (c)

Fig. 5. Autoclam permeability system (a) and its bonding (b) and bolt-on (c) application modes.

(a) (b)

Fig. 6. Bird Nest National Stadium, Beijing, China (a) including application of Autoclam system (b).

Against this background, the Science Bridge project encompasses technology transfer activities associated with three non-destructive tests and various sensor systems specifically developed at Queen's University for monitoring concrete properties and deterioration characteristics. Complementary investigations will be carried out by a range of project partners to compare field data obtained and predictions from relevant service life prediction models. Some of the testing techniques will also be used to quantify rates of deterioration during the active phase and estimate times to the end of service lives (see Fig. 3).

4.1. Limpet pull-off test

The limpet pull-off test (Fig. 4) measures the in situ tensile strength of cover concrete by applying direct tensile load via a disc bonded on the surface [8,9]. Based on empirical correlations, the compressive strength can be predicted from the pull-off strength. The test is also commonly used to determine the bond strength of concrete patch repairs [10,11], assess the effects of curing and carbonation of concrete and to determine the effect of micro-cracking. The main advantage of the pull-off test is that it is simple and quick to perform and no pre-planning is required to avoid reinforcement.

4.2. Autoclam permeability system

The Autoclam Permeability system (Fig. 5) was developed to measure the sorptivity, air permeability and water permeability of concrete cover on site [14]. Normally these tests are performed by isolating a test area of 50 mm diameter using either a bonding type ring or a bolt-on type ring (Fig. 5). Less permeable surfaces are tested with a larger contact area and normalising the data thus obtained to the standard 50 mm diameter. Although moisture influences the test results, research [15] has shown that the quality of concrete can be classified using the Autoclam permeability indices if tests are carried out when the internal relative humidity of concrete in the cover zone, up to a depth of 10 mm, is less than 80%. The test has been used to assess the quality of concrete in notable structures, such as Bird Nest National Stadium in Beijing (Fig. 6).

4.3. Permit ion migration test

Developed on the principle of ionic migration, the Permit ion migration test (Fig. 7) enables in situ determination of the resistance of concrete cover to chloride transport. Through extensive laboratory research, the test provides a coefficient of ionic transport in m^2/s [7,12]. It has also been established that Permit ion migration test results correlate well with conventional laboratory-based steady state diffusion and migration coefficients. The main advantage of this test is that it provides a migration coefficient without having to remove cores from a structure. Fig. 8 shows the Permit being used to assess the effectiveness of different methods of improving the chloride ion penetration resistance of the Qingdao Bay Bridge in China.

Fig. 7. Permit ion migration test.

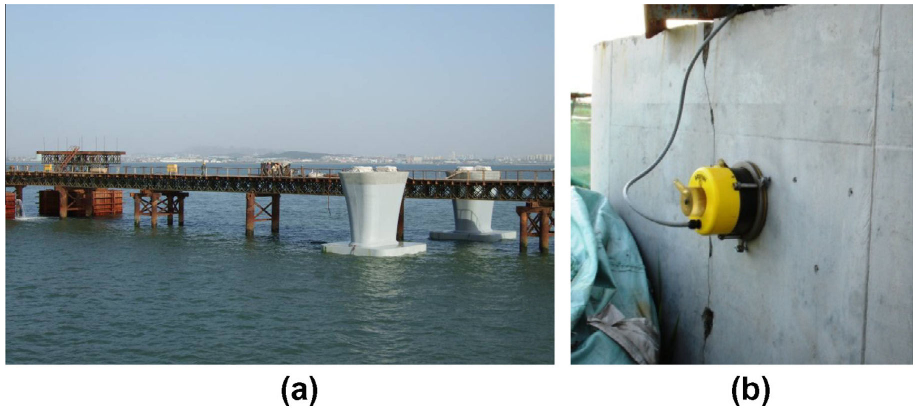


Fig. 8. Qingdao Bay Bridge, China (a) and application of Permit apparatus on bridge (b).

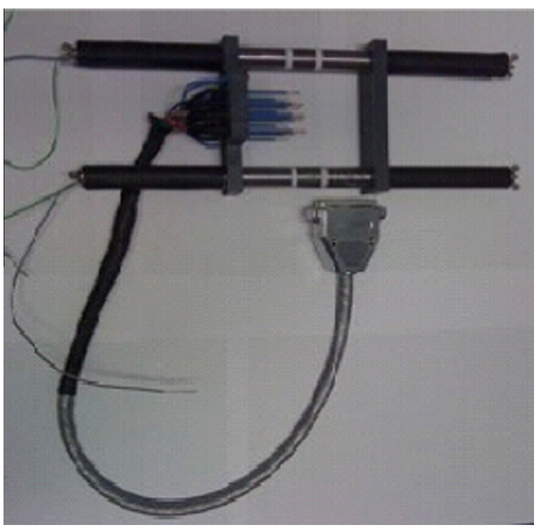


Fig. 9. Covercrete electrode array and corrosion probe.

4.4. Covercrete electrode array sensor

The primary function of the Covercrete Electrode Array developed by McCarter et al. at Heriot-Watt University, Edinburgh [16], is to provide real-time data on the condition of cover concrete and spatial distributions of cover-zone properties (Fig. 9). These sensors can be used to monitor moisture movement, chloride ingress and carbonation [17]. Currently the sensors are being investigated in a joint research project between Heriot-Watt University Edinburgh and Queen's University Belfast to develop performance-based specifications, along with application of the permeation tests developed at Queen's University. Fig. 10 shows an exposure site in Scotland where the sensors are being used to investigate the effectiveness of different types of cementitious materials against chloride ion penetration in a marine environment. Also shown in this figure is the full sensor system that allows remote sensing of data as required.

4.5. Exposure sites in China

In collaboration with the Science Bridge partners in China, different exposure sites will be identified in Tianjin, Hangzhou, Xi'An and Chongqing, as highlighted in Fig. 11, where the technologies from the UK will be demonstrated. The data thus obtained will be used in service life prediction models.

4.6. 'Flexiarch' as a sustainable form of construction for small to medium span bridges

Due to long service lives exhibited by masonry arch bridges (thousands of years as opposed to several decades for reinforced and pre-stressed concrete bridges), a novel flexible concrete arch system was developed at Queen's University Belfast [18]. This system has the potential to be highly sustainable due to the low or zero amount of steel reinforcement. As the arch system is

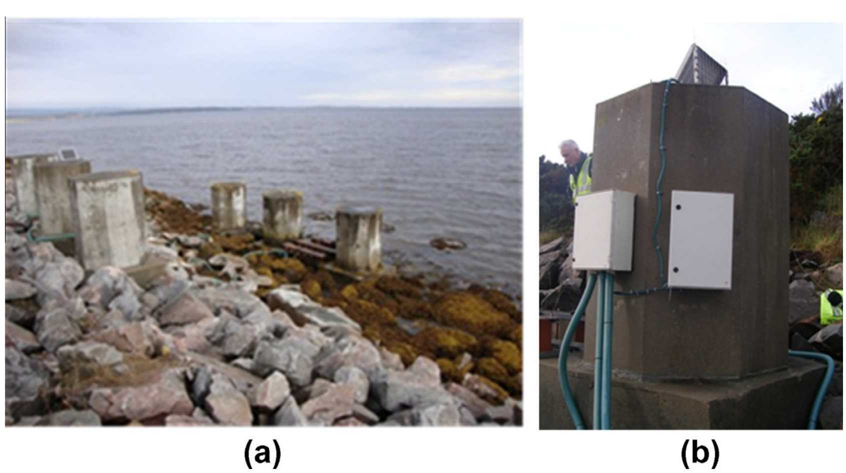


Fig. 10. Exposure site in Scotland (a) including remote data collection and solar power units (b).

Fig. 11. Location of field exposure sites in China (locations highlighted).

constructed in the form of a flat pack using a polymer grid reinforcement to carry the self weight during lifting, it is transported in flat packs, but behaves as a masonry arch once in place (Fig. 12). The main advantage of Flexiarch compared to more traditional system of masonry arch construction is elimination of centring during erection. The industrial exploitation of this innovative arch system has been undertaken by Macrete Ireland Ltd. Through Activity 2 of the Science Bridge, this novel system will be introduced in China.

5. Beyond the Science Bridge

5.1. Sustainability of the Science Bridge (short-medium term)

Through opportunities created by Activity 5 of the Science Bridge, it is anticipated that both UK and Chinese partners will establish ongoing participation in knowledge transfer programmes, training and education activities and commercialisation ventures. To encourage ongoing collaboration and encourage more wide-spread participation, joint centres were created. One such partnership formed is the UK–China Science Bridge Concrete Centre established at CRIBC in Beijing. With an intention to eventually operate on a membership basis, this Centre has already provided the platform for formal collaborative links to be forged between CRIBC, Queen's University Belfast, The Institute of Concrete Technology and the UK Concrete Society in terms of education and training, research and technology transfer activities.

5.2. Education and training (short-medium term)

A considerable number of Chinese construction labourers are frequently unskilled, untrained part-time workers from villages outside cities. Reflecting this position, it is recognised in China's 11th five-year plan that the scientific concept of development means China has to change from over-reliance on a cheap labour force, funds and natural resources, to well-educated workers and improvement of science and technology. The aim is a development

(a) (b)

Fig. 12. 'Flexiarch' system arriving on site (a) and completed bridge before covering with backfill (b).

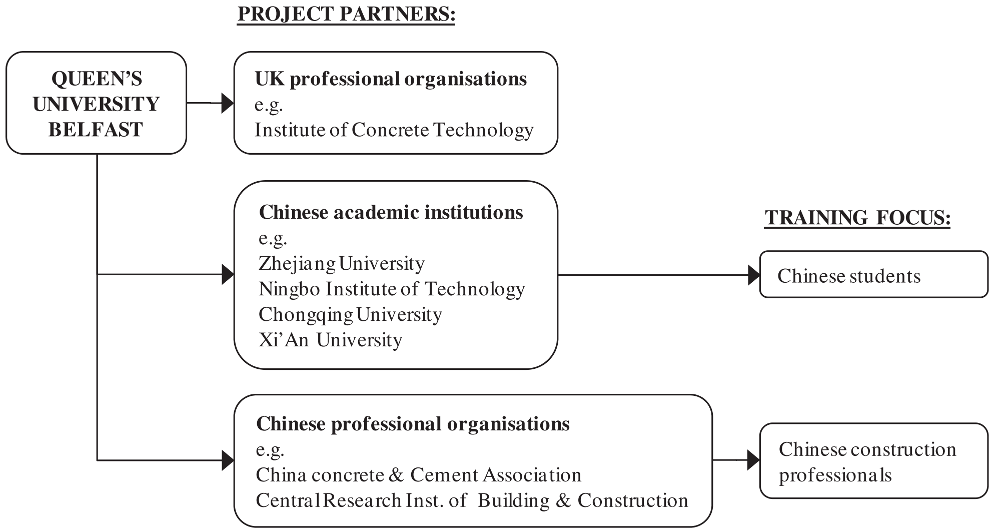


Fig. 13. Proposed overview of UK–China Education and Training Model.

mode that not only values quantity and speed, but also high quality and energy-efficiency [4].

Against this background, and building on Science Bridge activity areas 3–5, an identified immediate next step is to develop an academic- and industry-focused education and training model applicable to the Chinese construction industry. The focus of training will be concrete technology, durability and in situ materials' assessment and quality control. As shown in Fig. 13, the strategy is to partner with relevant professional and academic organisations in the UK and China to make this possible. The aim is to offer students and practicing professionals, alike, the opportunity to undertake state-of-the-art training packages leading to the attainment of internationally recognised professional qualifications. The aim of this work is to help improve the quality of concrete construction in China and, at the same time, enhance the domestic and international aspirations and prospects of participating individuals and companies.

5.3. International influence (long term)

To compliment the UK–China Science Bridge award, Queen's University has made a substantial financial commitment, along with the China Scholarship Council, to ensure up to 27 PhD bursaries for outstanding Chinese students. Students will join world-class research centres at Queen's University and participate in Science Bridge activities, undertaking research and innovation projects focusing on developing sustainable energy and built environment solutions. With a high proportion of these students predicted to return to China, the long term aim of this investment, and the Science Bridge project in general, is to develop an international network of highly trained professionals with strong links to Queen's University and the UK.

It is predicted this will assist with the project's overarching aim to benefit the UK from an enhanced uptake of its technology, knowledge and expertise through enhanced business opportunities and strengthened collaborations.

6. Conclusions

1. Changing international economic conditions and environmental circumstances not only pose considerable challenges for the built environment, but also present valuable opportunities to innovate, exchange ideas and strive towards a more advanced quality of life. Reflecting this and the need for strong technological linkages internationally, the UK government has provided financial support for UK institutions with existing research links to world-class universities and high-tech businesses in selective partnering countries. The remit of funded collaborations, or Science Bridges, is to accelerate the deployment of research knowledge, deepen and strengthen research links, enable the acquisition of new skills, and encourage mutual wealth creation. The UK–China Science Bridge at Queen's University is the sole project from all 10 awarded between China, India and the US with a construction focus.
2. While the Chinese construction industry continues to flourish, reliance on cheap, unskilled labour and the occurrence of premature deterioration of reinforced concrete structures is commonplace. As such, the integration of methodologies which enable fast and reliable quality control checks and ongoing structural health monitoring, have been identified as highly desirable. Equally, the introduction of efficient and resilient methods of construction aligns closely to current Chinese government strategy and policy on sustainable development.
3. The current focus of Queen's University's Science Bridge project is to integrate relevant UK-developed technologies and methodologies into the Chinese construction industry. With a focus on non-destructive testing methods (Permit, Autoclam, Limpet, embedded sensors) and an innovative construction methodology (Flexiarch), work will involve proof-of-concept studies undertaken by leading Chinese academic and industry partners. This work will be extended to include high-profile demonstration projects and ultimately the establishment of relevant Chinese codes and standards.
4. Ensuring sustainable UK–China linkages is an essential pre-requisite of all Science Bridge projects. A key route to achieving this as part of the Queen's University Belfast Science Bridge is to introduce an on-going programme of collaborative events focused on education, training and the exchange of knowledge between partners. In particular, targeted education and training initiatives are considered to successfully link like-minded organisations while helping to address core skills shortages.
5. Looking to the future of this UK–China Science Bridge, significant opportunity exists for more widespread collaboration in the area of the built environment between academic and industry organisations in the UK, Ireland and China. By evolving the project to encompass a broader spectrum of partners, innova-

tions, ideas and activities, the greater the likelihood of accelerating the deployment of knowledge, deepening and strengthening research links, enabling the acquisition of new skills, and encouraging mutual wealth creation.

Acknowledgements

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